EFFECT OF CONFIGURATION VARIABLES ON PERFORMANCE OF SOLID FUEL RAMJETS

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THESIS

EFFECT OF CONFIGURATION VARIABLES
ON PERFORMANCE OF SOLID FUEL RAMJETS

by

Clemens James Mady, Jr.

June 1977

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An experimental investigation into the effect of configuration variables on combustion performance in the solid fuel ramjet was conducted. The effect of air ducting methods on combustion efficiency was found to be dependent not only on the flow rates, momentum and geometry of the system but also on the composition of the solid fuel. High pressures and low air mass fluxes through the fuel grain affect the regression rate by altering

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Effect of Configuration Variables on Performance of Solid Fuel Ramjets

by

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Lieutenant, United States Navy
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ABSTRACT

An experimental investigation into the effect of configuration variables on combustion performance in the solid fuel ramjet was conducted. The effect of air ducting methods on combustion efficiency was found to be dependent not only on the flow rates, momentum and geometry of the system but also on the composition of the solid fuel. High pressures and low air mass fluxes through the fuel grain affect the regression rate by altering the heat transfer mechanism. Some air duct configurations were found to create a favorable environment for combustion pressure oscillations.

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I. INTRODUCTION

Several characteristics of the solid fuel ramjet indicate that it may be superior to other forms of propulsion for tactical weapons used at intermediate ranges and high speed. Having no moving parts, the solid fuel ramjet is simple and relatively inexpensive to fabricate. Weight of the system and its threat as a fire hazard are both decreased by use of the solid fuel.

To be used in a tactical situation, the solid fuel ramjet has to demonstrate combustions stability and efficiency over the expected operating envelope of altitudes and Mach numbers. It must also show performance comparable to that of liquid fuel ramjets and ducted rockets.

Combustion studies on the solid fuel ramjet have been underway at United Technologies-Chemical Systems Division (Ref. 1) since 1971. Initial work showed low temperature rise combustion efficiencies. The discovery of the rearward facing step at the combustor entrance as a flameholder was a significant step in solid fuel ramjet technology. Overall performance, however, was reduced by the high stagnation pressure loss produced by the rearward facing step. Further work by United Technologies in the field of flame stabilization involved various inlet designs including aerogrids, distorted flows, non-circular inlets and vortex generators. This effort has led to the development of low pressure loss inlets which appear to have minimized inlet step height requirements and eliminated most inlet distortion effects on flame holding.

stabilization, thereby reducing the pressure loss through the injector.

Work was also underway at the Naval Postgraduate School on the internal ballistics of the solid fuel ramjet. Jones and Netzer (Ref. 2) showed that inlet turbulence and distortion may have a significant effect on flame stability.

The solid fuel ramjet, which uses air as the oxidizing agent, is similiar to the hybrid rocket and has two distinct combustion zones (Ref. 3). Behind the step is the recirculation zone where an intense mixing of reactants and products takes place. The hot products ignite the reactants and combustion may in the limiting case approach that of a well-stirred reactor. This combustion region acts as the flame initiator for the combustion which takes place further down the fuel grain.

Downstream of the flow reattachment point a boundary layer develops. Here combustion is similiar to that of the hybrid rocket. A diffusion flame exists in the boundary layer between the fuel rich zone near the wall and the oxygen rich central air core. Heat is transported by convection and radiation to the solid surface which causes decomposition of the fuel. Studies have shown the rate of decomposition of the fuel is sensitive to the combustion pressure and the mass flux of the air.

The combustion process in the solid fuel ramjet is thought tc be mixing limited at combustion pressures greater than 10-15 psia for all-hydrocarbon fuels (Ref. 4). However, this remains to be verified and other fuels have demonstrated behavior more characteristic of kinetically controlled combustion. Unburned gaseous fuel escapes from under the flame at the aft end of the fuel grain and results in decreased combustion efficiency. Temperature rise

efficiencies based on both thrust and pressure measurements were found to be correlated by parameters reflecting the rate of mixing. Work by United Technologies showed that combustion efficiency can be improved by increasing the rate of mixing between the fuel rich boundary layer and the central air core. However, too rapid mixing may quench the reaction and further reduce combustion efficiency.

Work at the Naval Weapons Center, China Lake (Ref. 5) and at United Technologies (Ref. 4) has further shown that combustion is increased with the use of an aft mixing chamber. Intense combustion with strong gas temperature increases were observed for L/D (length to diameter of mixer) ratios up to 3.3.

The use of aft-end mixing devices to improve combustion efficiency is an area of recent interest in solid fuel ramjet technology. As another means of promoting mixing, the bypassing of a portion of the inlet air around the fuel grain and dumping it into the aft mixing chamber is being re-evaluated. A meteorlogical sounding rocket capable of an altitude of 200,000 feet was designed and built by Anderson, Greenwood and Co., Houston, Texas in 1961 (Ref. 6). The MET JET employed a ramjet using a magnesium and magnesium-aluminum alloy epoxy-metal charge. Eighty-five percent of the inlet air was bypassed around the fuel grain to mix in an afterburner section with the fuel rich primary flow.

In the bypass systems, the flow rates into the fuel grain inlet and aft mixing section are critical factors in determining combustion efficiency. Bypass air flow of too low a percentage of the total air mass flow or of too low momentum may have negligible effect on the combustion efficiency. Bypass air of too high a flow rate or momentum may have a negative effect on the combustion process. The

bypass air is of appreciably lower temperature than the species which exit from the fuel grain, and air injected at too high a rate may cool the process sufficiently to affect the kinetics of the reaction. Furthermore, the combustion process in the aft mixing chamber may also be a function of the axial and radial positions and of the angular orientations of the aft dumps.

This research was concerned with the use of bypass air flow as a means of improving combustion efficiency. Mass flow rate, momentum, and the number, location and angular orientation of the aft dumps and the use of an orifice plate between the fuel grain and aft mixing chamber were evaluated to determine their effects on the combustion process.

Polymethylmethacrylate (PMM) was used as a fuel in this research. PMM becomes a monomer in the gaseous phase while currently used hydrocarbon fuels are polymers.

II. METHOD OF INVESTIGATION

Experimental firings of the solid fuel ramjet were conducted using polymehtylmethacrylate fuel grains while varying primary-to-bypass air flow ratios and aft dump geometry. The tests were performed to provide data for the study of the effect of bypass air flow on combustion efficiency.

III. DESCRIPTION OF APPARATUS

A. RAMJET MCTOR

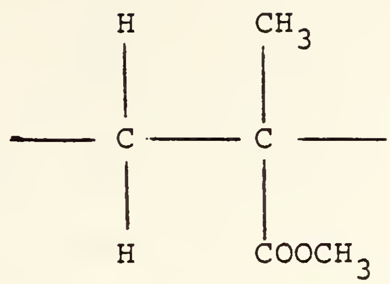
The solid fuel ramjet motor (Fig. 1), with the exception of the bolts,was made of stainless steel. The first two sections, the head end assembly and the step insert section, were those previously used by Boaz and Netzer (Ref. 3). The other two sections were the fuel grain and the aft mixing section.

The head end assembly contained the inlet to the ramjet motor and the ports for the ignition system oxygen and methane. Also in the assembly were mounted the two Champion Z7 spark plugs used in the ignition system, an iron-constantan thermocouple to measure inlet air temperature and a pressure tap connected to a Wiancko 0-200 psig pressure transducer to measure inlet pressure.

The step insert section held an insert with an inside diameter of .50 inches and was also used for mounting the front end of the fuel grains.

The fuel grains were made of Polymethylmethacrylate, chosen because of its previous use in the study of internal ballistics of solid fuel ramjets at the Naval Postgraduate School and because it facilitates flame observation.

PMM is a polymer of the form:



The stoichicmetric equation for complete combustion with air is:

$$C_5H_8O_2 + 6O_2 + 22.5N_2 \rightarrow 4H_2O + 5CO_2 + 22.56N_2$$

The theoretical equilibrium composition and temperature for combustion at different air-fuel ratios, inlet air temperatures and combustion pressure were obtained from the Naval Weapons Center, China Lake, California.

The PMM was cut into fuel grains 12 inches long and 3.75 inches square. The front and rear of the grains were machined to an outside diameter of 3.50 inches to fit into the step insert and aft mixing sections where "O" rings were used for the seal. With the exception of one run, all grains were bored to an inside diameter of 1.50 inches. This provided an air injector step height to grain port diameter ration, h/D, of 0.333 (or equivalently a port to injector area ratio of 9.0).

The aft mixing section fit to the rear of the grain and was tied to the step insert section with four 3/8-inch steel

rods. The mixer was 6.22 inches long and had an $(L/D)_{mixer}$ of 2.93. It was comprised of five sections to facilitate the changing of design variables. The first section, 1.688 inches in length, was used to mount the mixer to the grain and to hold the mixing orifice plate. The plate had an outside diameter of 3.0 inches and an inside diameter of 1.50 inches, and when installed provided a constant L_{mixer}/D_{port} for flow into the mixing section.

The second section was 2.0 inches long and contained the four inlets for the secondary or bypass air flow. The inlet diameters were 1.063 inches with plugs available to reduce the diameters to 0.813, 0.751, 0.574 or 0.25 inches, or to seal the inlets off entirely.

The third section, also 2.0 inches long, was used in conjunction with the second section to alter the axial position of the bypass air inlets.

The fourth section, 1.438 inches in length, contained two pressure taps located 180 degrees apart which were connected to a Wiancko 0-150 psig pressure transducer to measure combustion pressure.

The last section of the aft mixer was the end plate containing the converging-diverging nozzle. The nozzle consisted of a circular arc converging section, a straight throat section of constant diameter and a conical exit section with a half angle of 30 degrees. The nozzle throat diameter was 0.75 inches, which provided a port-to-throat diameter ratio of 4.0.

The aft mixing section was held together by four 3/8 inch stainless steel rods with "O" ring seals between the

individual sections and was supported by a mounting flange on the test stand.

B. IGNITION SYSTEM

Oxygen and methane in two high pressure tanks were delivered at 700 psig through two needle valves to inlet ports in the head end assembly. A Model T ignition coil and transformer supplied the spark to the two Champion Z7 spark plugs located downstream of the inlet ports.

C. NITROGEN PURGE AND AIR COLLING SYSTEM

To extinguish the flame at the end of a firing, nitrogen was fed momentarily into the system (upstream of the head assembly section) from two high pressure bottles at 80 psig. The motor was then cooled with air from a low pressure compressor.

D. AIR FLOW CONTROL

Aif flow rates through the primary and bypass lines were measured by two standard ASME orifices. The primary had flange taps and the bypass had taps at 1 D and 1/2 D. Primary and bypass flows were controlled by manually operated valves. Primary air was either vented to the atmosphere or routed through the motor by two pneumatically operated Jamesbury ball valves working together. Bypass air was continually passed through the aft mixing section.

E. DATA ACQUISITION

Temperatures at the orifices and the inlet to the motor were measured by iron-constantan thermocouples and recorded on a 0-600°F strip chart recorder.

The upstream pressure of the primary orifice was measured by a 0-500 psig Taber pressure transducer while a 0-200 psig Wiancko pressure transducer was connected upstream of the secondary orifice. Colvin 0-35 psi differential pressure transducers were used to measure the pressure drops across the two orifices. The inlet pressure to the motor was measured by a 0-500 psig Wiancko pressure transducer, and a 0-120 psig Wiancko pressure transducer was used to measure the chamber pressure in the aft mixing section.

All transducer outputs, along with a 5 cycle per second timing signal and an ignition pulse, were connected to a Honeywell Model 2106 Visicorder.

F. AIR FEED SYSTEM

A Pennsylvania air compressor capable of 700 scfm supplied air at a pressure of 150 psia. A portion of this air was routed through the heat exchanger of a Polytherm air heater and provided non-vitiated hot air. The air heater had a capability of 1.75 pounds per second at 150 psia and 1000°F.

Two valves and a temperature controller mixed the hot air with the remaining cold air to supply air at the desired temperature. Air flow was controlled by a manual gate valve

before leaving the pump room. In the test cell the flow of air was controlled by an electrically operated gate valve before being split into primary and secondary air flows upstream of the orifice flow meters. Figure 2 presents a schematic of the test apparatus. Figures 3 through 6 present photographs of the ramjet motor and test stand.

IV. EXPERIMENTAL PROCEDURE

All test firings were performed in the jet engine test cell at the Naval Postgraduate School. Data for calculating temperature rise efficiencies based on combustion pressure were obtained while varying primary and bypass air flow rates and bypass dump geometry. Nominal air flow rates were 0.1 and 0.2 lbm/sec for non-bypass runs and 0.2 lbm/sec for runs using bypass. In the bypass runs, primary-to-bypass air flow ratios employed were 65/35, 50/50 and 35/65.

Two and four aft dumps, ranging in diameter from 0.25 to 1.063 inches, were used. Dump size was varied to allow different total and individual air flow momentum in the aft dumps. Momentum relations for all tests were compared to a reference condition which used a bypass air flow rate of 0.1 lbm/sec and two dumps with diameters of 0.813 inches.

With the exception of the runs using swirl, all dumps were oriented perpendicular to the centerline of the aft mixer. With swirl, the dumps were oriented to inject the air flow tangentially to the circumference of the mixer. Test firings through run no. 8 were made without the aft orifice mixing plate. The remaining runs (beginning with no. 9) all used the aft orifice.

Tests were conducted with the dump section in both positions two and three of the aft mixing chamber to observe the effect of air injection prior to and after the predicted primary flow reattachment point (Ref. 7).

The nozzle for all PMM firing runs had a diameter of 0.75 inches. For the expected combustion temperatures and planned air flow rates, this nozzle kept the combustion pressure low enough to maintain choked flow across the upstream air flow control valve.

The majority of the test firings were made using a nominal inlet air temperature of 70°F. For those using the Polytherm air heater, two to three hours were allowed for the temperature to stabilize at the ramjet inlet and in the bypass air line. The low flow rates to the motor necessitated this delay.

The weight, length and inside diameter of the fuel grains were measured prior to being mounted in the motor. The ignition sequence normally lasted for six seconds. An average of three seconds was required for the ignition flame to propagate from the head end assembly into the fuel grain. After five seconds, the air was directed through the ramjet motor. Ignition was continued into the first second of the run to insure that combustion would be sustained. Total time of the ignition flame in contact with the fuel grain amounted to approximately three seconds. Two tests were made using only the ignition system in order to determine the rate of consumption of the PMM grains during the oxygen-methane ignition. These data were used to correct the initial weight of the fuel used in the efficiency calculation.

Combustion normally lasted for forty-five seconds. The motor was extinguished at the end of each run by simultaneously venting the air to the atmosphere with the Jamesbury ball valves and actuating the nitrogen purge system. Low pressure air was then blown through the motor for cooling. After a sufficient period of time, the fuel

grain was removed and the final weight and aft end inside diameter were measured.

V. RESULTS AND DISCUSSION

A. DATA REDUCTION METHODS

Thirty-three hot firing PMM tests were conducted. Measured and reduced data for the runs in which combustion was sustained are tabulated in Appendix A.

Data reduction was accomplished on the Hewlett-Packard 9830 using a basic language program. Combustion efficiencies were based on the total temperature rise from just upstream of the rearward facing step to the aft mixing section (Ref. 8). Inlet total temperature was derived from the measured inlet static temperature.

Polynomial regressions were performed on the data from the Naval Weapons Center, China Lake. Equations for the ideal combustion temperature, gas constant and ratio of specific heats based on equilibrium calculations are presented in Appendix B.

Actual combustion temperature was derived from the measured static pressure in the aft mixer. With choked flow across the exit nozzle, the mach number in the mixing section was obtained from the isentropic relation for A/A^*. With the air and fuel flow rates, Mach number and pressure known in the aft mixer, combustion temperature was calculated using the continuity equation.

The stagnation pressure in the aft mixing section was derived from the measured static pressure and was used to calculate the actual C^*. Ideal C^* was calculated using the ideal combustion total temperature. C^* efficiency is the ratio of the actual to ideal C^*.

The actual composition of the exit products of the SFRJ are unknown. To obtain a more realistic value for the efficiency of the motor, a second calculation of efficiencies was performed. It was assumed that inefficiency in the SFRJ combustion was due to incomplete combustion and therefore the species that would be present from complete combustion were only present in a percentage equal to the initially calculated efficiency. The remaining fraction of exit products was assumed to be comprised of unreacted air and fuel in a percentage equal to the air-fuel ratio. Based on this assumption, a new average molecular weight for the combustion products and a new gas constant were computed. This new value was then used to re-calculate the efficiencies. This resulted in a higher average molecular weight and higher efficiencies. Both values for the temperature rise combustion efficiencies and the C^* efficiencies are included in Appendix A. Further data reductions, correlations and discussions were based on the corrected combustion efficiency.

Regression rate was calculated based on weight loss of the fuel. The inside diameter of the aft end of the fuel grain was also measured before and after each firing. However, as with Boaz and Netzer (Ref. 3), it was found that weight loss gave a better value of regression rate than

the method based on aft end diameter change, due to the non-uniform regression along the length of the grain.

The expected uncertainties in the experimental results were calculated using the method of Kline and McClintock (Ref. 9). These uncertainties are given in Table I.

B. REGRESSION RATE

Several runs were made without using bypass air. These showed the dependence of the regression rate, $\dot{r}$ (in/sec) on combustion pressure, P (psia) and average mass flux of air, G (lbm/in^2-sec) to be:

$$\dot{r} = .0043P^{.29}G^{.38} \qquad (1)$$

A plot of the regression rate versus this emperical regression rate equation for the 0.2 and 0.1 lbm/sec non-bypass runs made with cold inlet air is shown in Figure 7.

In their work with PMM, Boaz and Netzer (Ref. 3) had shown a regression rate dependence of the form:

$$\dot{r} = CP^{.51}T^{.34}G^{.41} \qquad (2)$$

where C is a constant and T is the inlet air temperature.

Insufficient runs were made in this investigation at other than ambient inlet temperature to calculate a temperature dependence for the regression rate. The above equations for regression rate agree closely for the dependence on G. The dependence on pressure was significantly less in this study. In the work of Boaz and

TABLE I

ERROR ANALYSIS

Variable	Percent Error
Air Weight Flow Rate	1.1
Fuel Weight Flow Rate	0.4
Air Flux Rate	1.2
Combustion Efficiency	7.0
Regression Rate	1.2
C^* Efficiency	2.3
Actual Combustion Temperature	5.6
Ideal Combustion Temperature	1.7

Netzer, chamber pressure was varied intentionally from 37 to 108 psia by varying the throat size. In this study pressure varied between 33 and 63 psia only as a result of varying combustion efficiency and G.

With the application of bypass air, the dependence of regression rate on pressure and air flux rate was altered. In figure 8 are plotted the cold 0.2 lbm/sec non-bypass cases and the bypass runs made with 0.2 lbm/sec total air flow rate and individual dump momentum equal to that of the reference condition. The reference condition, as described in the chapter on Experimental Procedure, is a bypass air flow rate of 0.1 lbm/sec and two dumps with diameters of 0.813 inches. This corresponds to a dump momentum to fuel grain port momentum ratio of approximately 0.5. A slightly stronger dependence on pressure was shown, while regression rate indicated very little or no dependence on air flux rate for the values tested. Here regression rate took the form:

$$\dot{r} = .00116P^{.42}G^{.003} \qquad (3)$$

In the bypass situation, the mass flux through the grain is low but the pressure is maintained high due to the total mass flux through the nozzle throat. However, correcting the regression rate for the increased pressure per equation (2) does not result in regression rates as high as the experimental data. In addition, regression rates based on weight and diameter agree, indicating that the change does not result from different combustion behavior within the aft mixing chamber. These conditions of low G and high P minimize the convective heat flux to the fuel surface but maximize radiative heat flux. Thus, the regression rate becomes sensitive to pressure and mixture ratio. PMM-Air combustion at the high air mass fluxes has both radiative and convective transfer to the surface as indicated by equation (1). However, the pressure dependence could also

result from kinetic controlled combustion. For the bypass situation, PMM-Air combustion appears to become dominated by radiative heat transfer as indicated by equation (3). For lower G the regression rate increases relative to the air flux, i.e., more unburned fuel exists within the fuel grain underneath the diffusion flame within the thicker boundary layer; Thus, more gas with radiative properties is present.

C. COMBUSTION EFFICIENCY

The effects of air mass flux and bypass ratio separately on combustion efficiency were then studied to determine the overall effect of bypass air flow on combustion performance.

In Figure 9 are plotted the cases from both Figures 7 and 8. As can be seen from this figure and the data of Appendix A, the use of bypass air flow in a solid fuel ramjet using Polymethylmethacrylate as a fuel has the effect of reducing combustion performance. For the non-bypass runs, a decrease in air flow brings a decrease in combustion efficiency. While maintaining the same air flux through the grain, injecting bypass air into the mixing section brings a further decrease in performance. Decreasing or increasing air flux through the fuel grain while maintaining the same total flow rate in the bypass case also brings about a corresponding change in combustion efficiency.

The same conclusion can be drawn from the study of efficiency as a function of bypass ratio. To prevent singularities in the multiple regression analysis of the data, the bypass ratio was defined as the ratio of primary air mass flow rate to the total air mass flow rate. An increase in bypass ratio in this study means an increase in the percentage of air flow through the fuel grain and a

decrease in the percentage of air flow through the aft mixing dumps.

As indicated by Figure 10, which again plots the cold 0.2 lbm/sec non-bypass cases and the 0.2 lbm/sec reference bypass momentum cases, increasing the percentage of total air flow through the fuel grain brings an increase in combustion efficiency. The best performance occurs in the limiting case of all of the air flow through the grain and no bypass.

Figure 11 shows a correlation between regression rate and the bypass ratio. The increase in regression rate was expected, as an increase in bypass ratio results in both an increase in air mass flux through the fuel grain and an increase in combustion pressure.

To further study the decrease in performance found when using bypass, other test conditions were considered. Runs 5 and 7 were run with the dumps located behind the aft mixing chamber reattachment point. There was only a slight decrease in combustion efficiency (81.2%) over that of identical runs in the forward position (83.0%). This difference is negated by the possible experimental error involved in calculating combustion efficiency. In fact, it should be mentioned that temperature rise efficiencies based on pressure are prone to error, since uncertainty in efficiency goes as the square of the uncertainty in the pressure measurement.

Three runs were made varying the momentum of the individual dumps from the reference condition. Small changes in momentum had no effect. Varying the momentum from 0.5 (run 17) to 2.0 (run 24) gave efficiencies of 82.5% to 82.8% compared to a reference run efficiency of 83.0%. However, when a significantly large increase in momentum was

effected (run 29), the combustion performance showed a noticeable decrease (72.8%).

Only limited data were taken (runs 18,19,20) for other than two dumps at 180 degrees. However, the data showed that with low momentum, two or four dumps spaced 90 degrees circumferentially reduced the combustion efficiency. Four ninety degree dumps with high momentum did not change the combustion efficiency significantly.

The last variation in geometry studied was the use of swirl on the aft dump process. This was accomplished by injecting the dump air with a tangential velocity component. The solid fuel ramjet motor was run without fuel grain ignition, both with and without swirl, to determine the effect of the induced vorticity on the effective exit nozzle diameter. Decreasing the effective nozzle diameter would increase the combustion chamber pressure and give false indications of higher efficiency. The swirl was found to not affect the effective throat diameter. Two test firing runs were made with swirl, giving an average combustion efficiency of 86.4% and the highest performance of any bypass firing run.

Every form of bypass used showed a decrease in combustion performance. This indicates that the decrease in performance is due to the effect of the bypass air flow on the kinetics of the combustion process within the aft mixing chamber. An analysis of the effects can lead to a better understanding of the internal ballistics in the aft mixing chamber. Equal decreases in performance were reached with the dump air injected both behind and in front of the reattachment point. This indicates that there is a significant amount of the combustion process still taking place downstream of the reattachment point in the aft mixing chamber. This agress with the temperature data presented by

Schadow (Ref. 10) for an all-hydrocarbon fuel. In the case of PMM, the light weight unburned hydrocarbons that enter the aft mixing chamber apparently burn most completely when allowed to react slowly with the available oxygen in the hot flow through the core of the fuel grain.

The possibility of the temperature of the air entering the aft mixer causing reduced combustion efficiency was considered. In run number 9 the temperature entering both the grain and aft mixer was increased from approximately 520°R to 705°R. The combustion efficiency did not change significantly, indicating that for PMM-Air combustion the dump air temperature is probably not as important as the quantity and temperature of the unburned fuel and the mixing rate.

In the region in front of the reattachment point, the less that was done to disturb the flow resulted in better performance. In the case of swirl, where the bypass flow remained close to the wall and within the recirculation zone, bypass efficiency was maximized. When the bypass momentum was increased to where the flow disturbed the fuel rich layer between the recirculation region and the air rich central core, performance decreased. This again indicates that a major portion of the combustion process takes place along this fuel rich layer or that the process downstream is highly dependent on the high temperatures in this layer. It also indicates that the combustion mechanisms around this layer are more important than those which occur within the recirculation region.

Although the use of Polymethylmethacrylate as a fuel in a solid fuel ramjet using bypass has not shown an increase in performance, it has given evidence as to the internal combustion processes within an aft mixing chamber.

It is known that the use of bypass improves performance in solid fuel ramjets using all-hydrocarbon fuels. In the case of oxygen-containing fuels and for fuels which decompose into monomers or small hydrocarbon molecules (such as PMM), results indicate that the fuel burns most efficiently without bypass.

The use of bypass systems has meant an increase in weight, cost and complexity of the solid fuel ramjet. In addition, they may introduce combustor-feed system coupling. The use of a fuel which has sufficient density impulse, regression rate and flammability limits to minimize inlet total pressure losses has led to the use of all-hydrocarbon fuels. Although PMM does not meet the criteria for a good fuel, the results of this study indicate that future fuel studies may be fruitful if directed toward ones which contain low percentages of oxidizer and/or substances which unzip the hydrocarbon chain.

D. COMBUSTION PRESSURE OSCILLATIONS

In the non-bypass test runs, the inlet and combustion pressures exhibited a steady, small amplitude (approximately 2% of chamber pressure) oscillation of approximately 150 Hz. In the bypass runs of reference condition momentum, the same oscillation appeared though of considerably higher amplitude (approximately 30% of chamber pressure). Computations made from the dimensions of the ramjet motor and the associated ducting indicated that this oscillation was probably not a combustor-feed system instability.

In the cases of low or very high aft dump momentum, a second oscillation appeared along with that previously mentioned.. This oscillation was of very low frequency

(1 Hz.) and large amplitude (approximately 20% of chamber pressure) and may be connected with behavior within the mixing chamber recirculation zone. It is possible that the aft dump process slows the reaction in the fuel rich shear layer passing by the recirculation zone (by direct mixing, displacement of the entire recirculation zone or increased mixing between the fuel and air exiting the fuel grain). When this happens, combustion pressure could drop, followed by a decrease in regression rate. Then, as the mixture ratio in the shear layer becomes closer to stoichiometric, the reaction rate and temperature would increase, causing an increase in combustion pressure. This pressure increase would increase the regression rate to complete the cycle. This mechanism is quite speculative and others are equally plausible. However, the bypass-generated very low frequency pressure oscillations do appear to be coupled to the fuel regression rate.

VI. CONCLUSIONS

The use of bypass air flow in the solid fuel ramjet has a significant effect on combustion performance. Air flow injected into the aft mixing chamber has a more pronounced effect on the combustion process when a high enough momentum is provided for the bypass air to reach the fuel rich shear layer trailing from the port of the fuel grain. Bypass air which remains in the recirculation zone also effects combustion, but not to as great an extent.

A significant amount of combustion occurs downstream of the reattachment point. This is evidenced by the effect of bypass air injected into this region, and is supported by data from previous work done on flows in aft mixing chambers.

Bypass air injected into the aft mixing chamber has an effect on the regression rate upstream in the fuel grain. At high pressures and low air mass flux rates, the principal mechanism for wall heat flux became radiation, and resulted in the regression rate becoming insensitive to G. For PMM, regression rate takes the form:

$$\dot{r} = .00116P^{.42}G^{.003}$$

While known to be advantageous with all-hydrocarbon fuels, the use of bypass air flow with fuels containing oxygen (or those which decompose into monomers or small hydrocarbon molecules) appears to slow the kinetics of the combustion process and lower performance. Fuels containing

their own oxidizer or substances to unzip the hydrocarbon chain show definite possibilities for high performance and an alternative to the use of bypass systems.

With the use of bypass systems, it is possible to set up not only combustor-feed system type oscillations but also instabilities dependent on the effect of the bypass flow on the combustion process within the aft mixing chamber and on the fuel regression rate.

VII. SUGGESTIONS FOR FUTURE WORK

Additional experimental studies are required to better understand the internal ballistics of the aft mixing section of the solid fuel ramjet. In the area of bypass systems, more work is needed in studying the combustion process ahead of and behind the aft mixing chamber reattachment point. Specific experimental studies should include: a) aft dump flow rates and momentum, b) alternate fuels, c) the effect of axial position of the aft dumps and d) the use of longer mixing sections to allow more time for complete combustion, with a consideration of the tradeoff between added weight and increased efficiency. Experimental and analytical work are required on the feasibility of developing a solid fuel ramjet fuel which will supply the necessary performance characteristics for use in a propulsion system without the need for bypass.

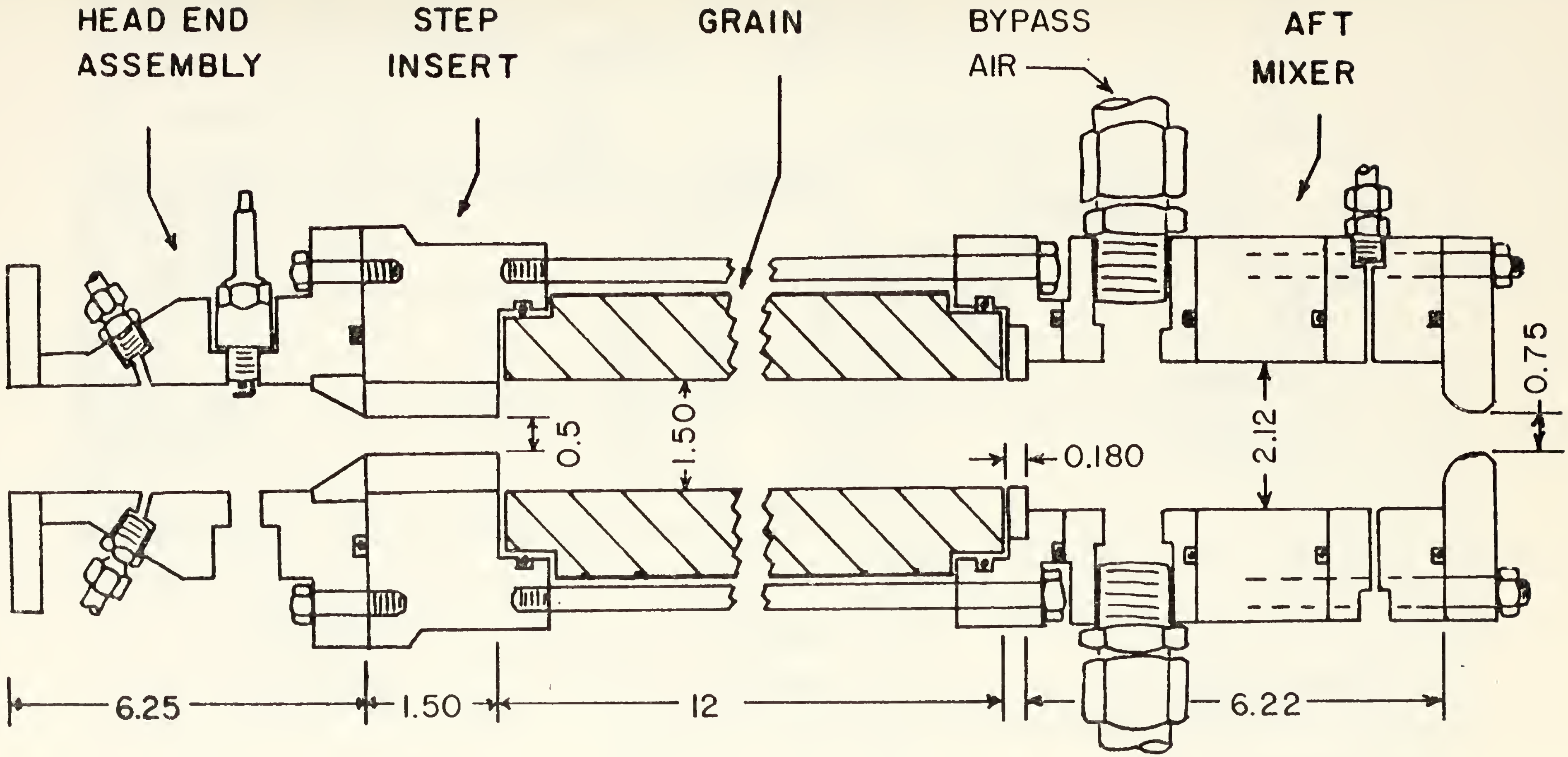


Figure 1 - SOLID FUEL RAMJET MOTOR

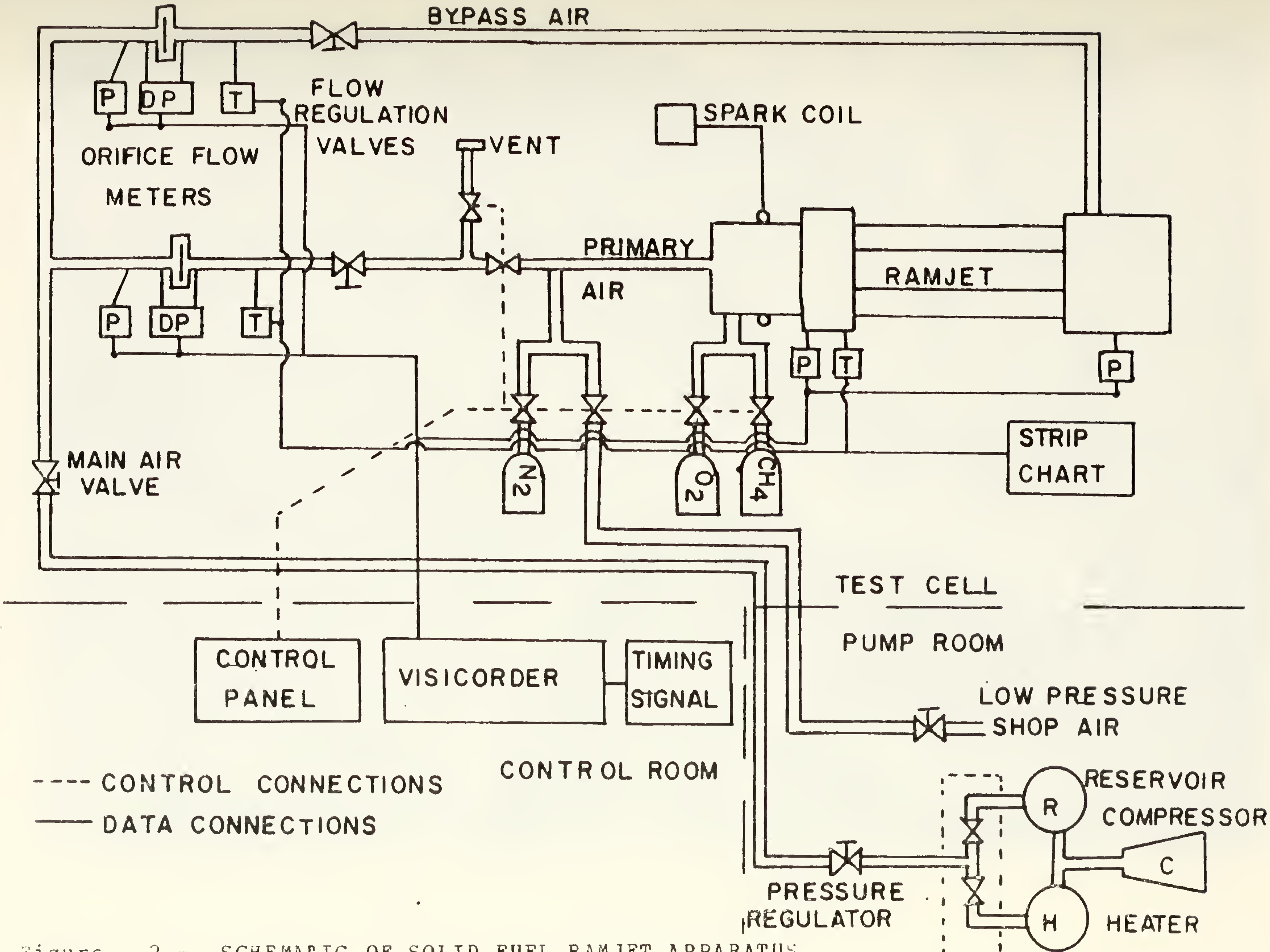


Figure 2 - SCHEMATIC OF SOLID FUEL RAMJET APPARATUS

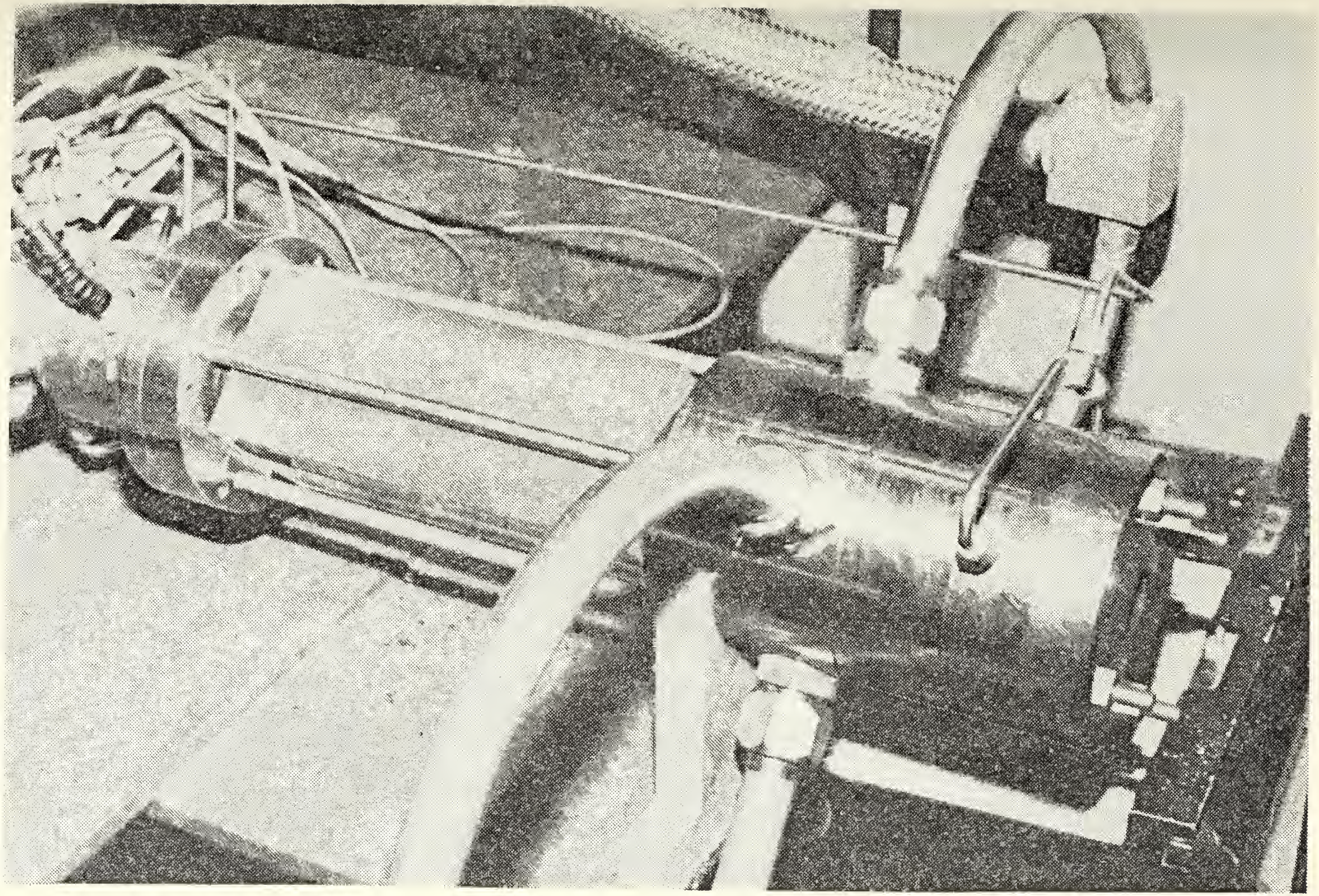


Figure 3 - RAMJET MOTOR ON TEST STAND

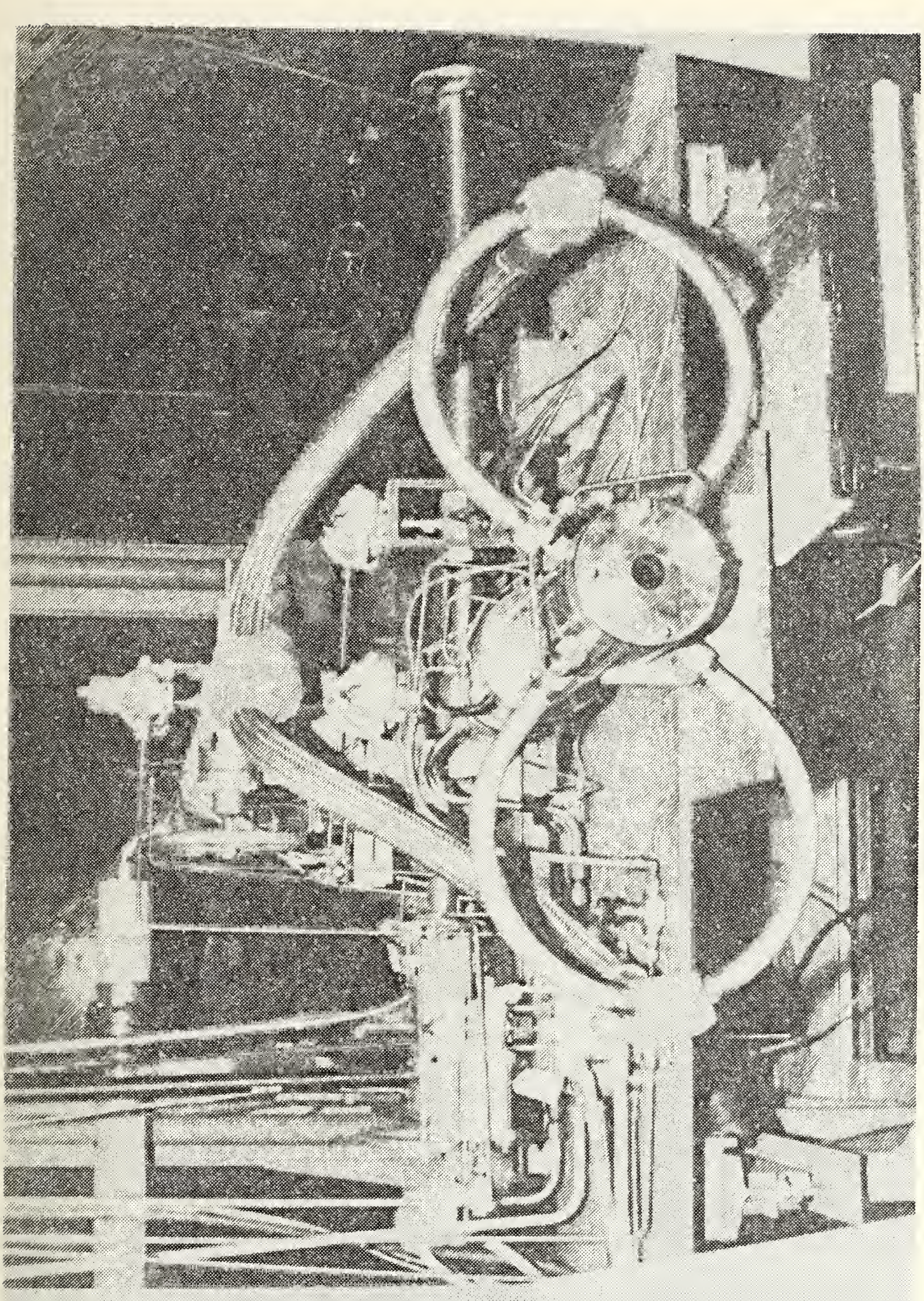


Figure 4 - TEST STAND

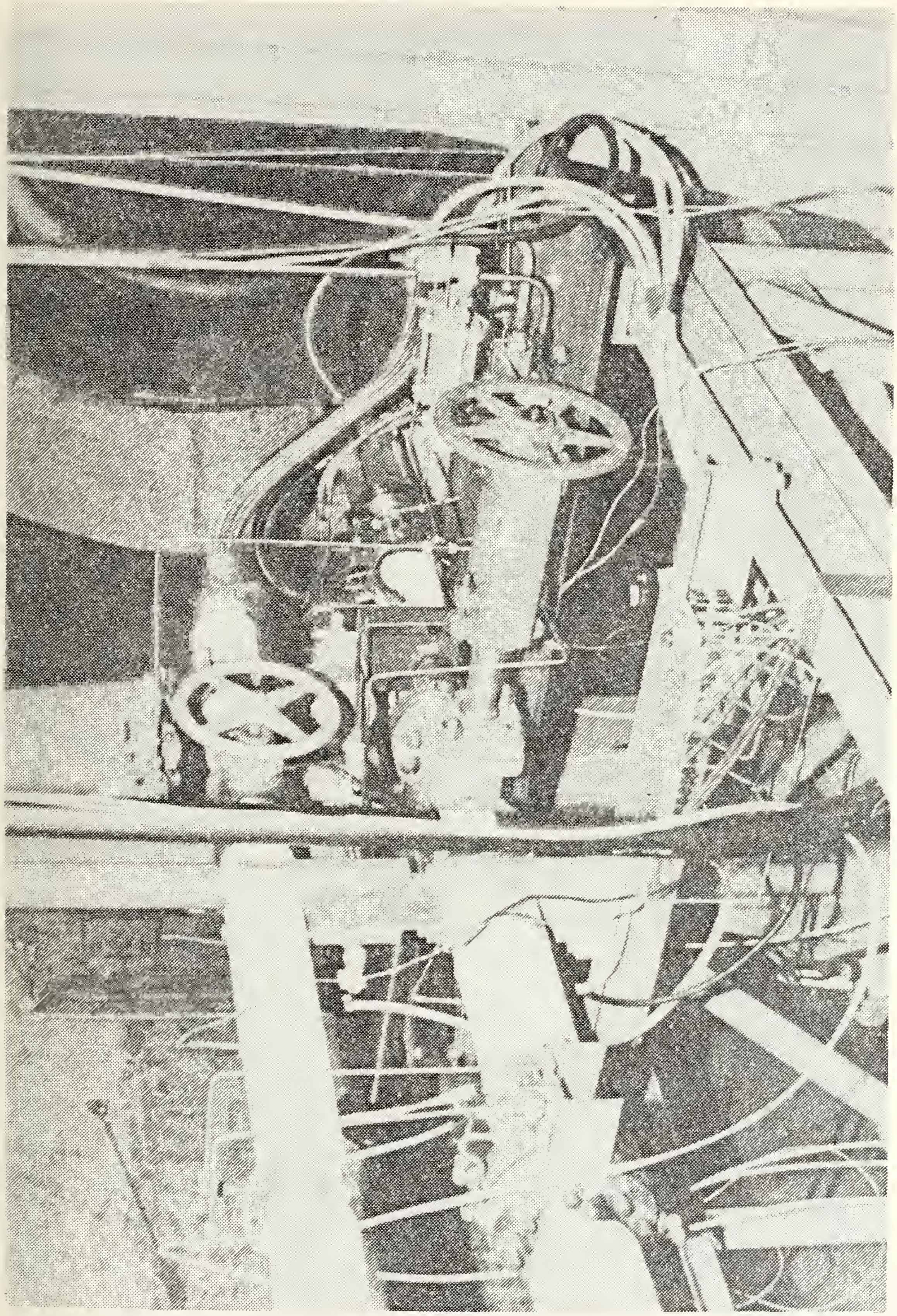


Figure 5 - TEST STAND

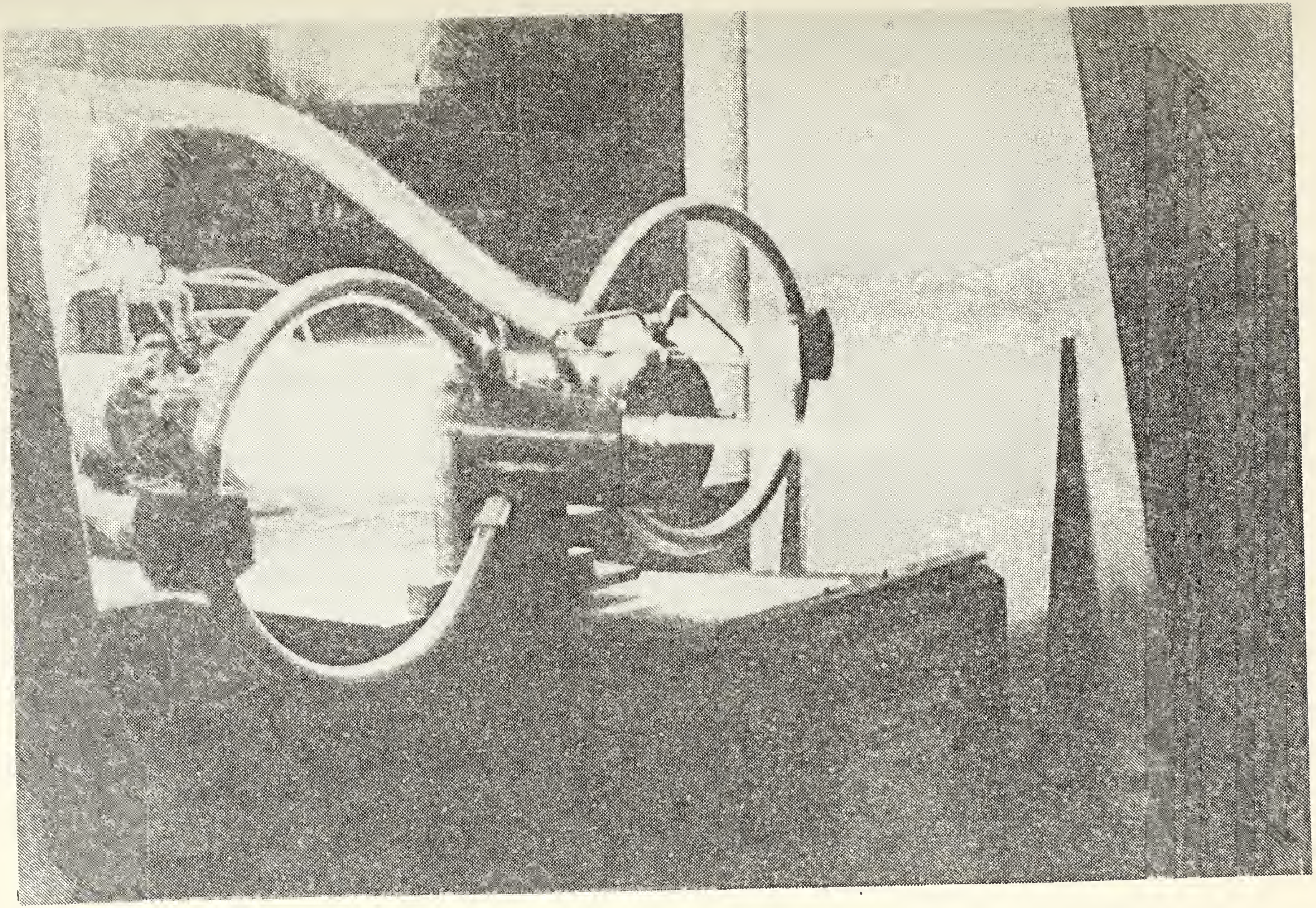


Figure 5 - RAMJET MOTOR FIRING

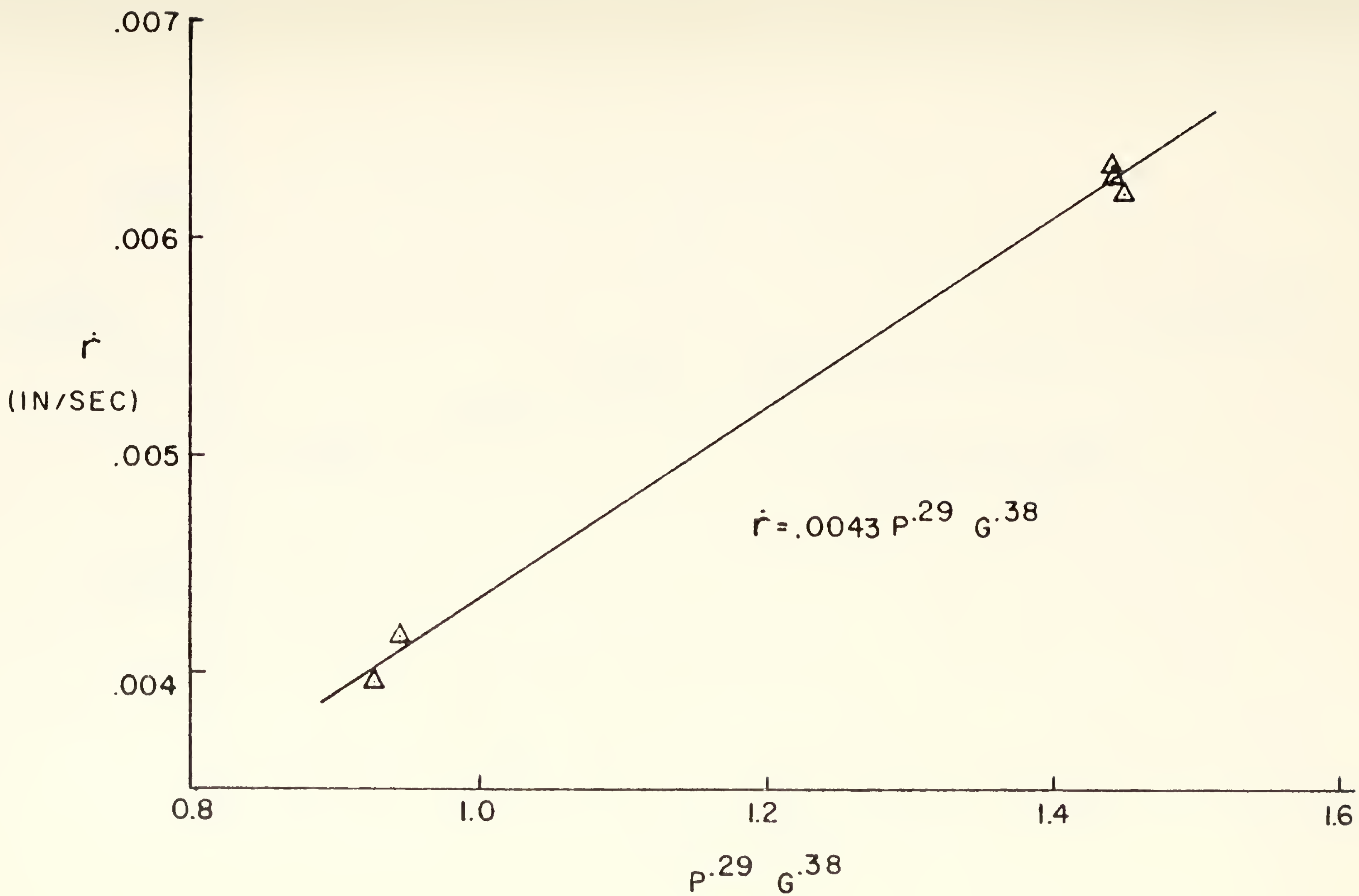


Figure 7 - REGRESSION RATE-NON BYPASS

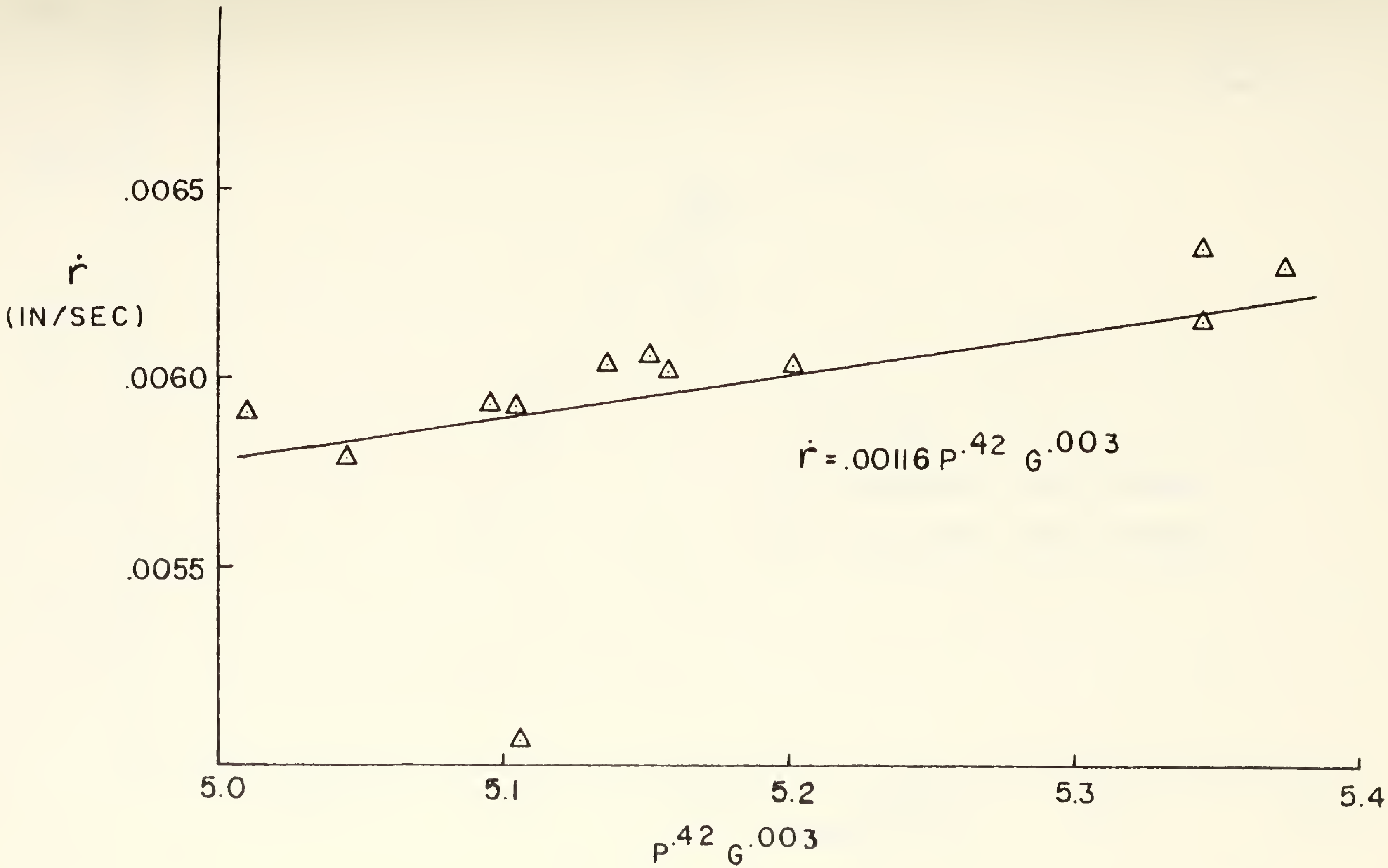


Figure 8 - REGRESSION RATE-BYPASS

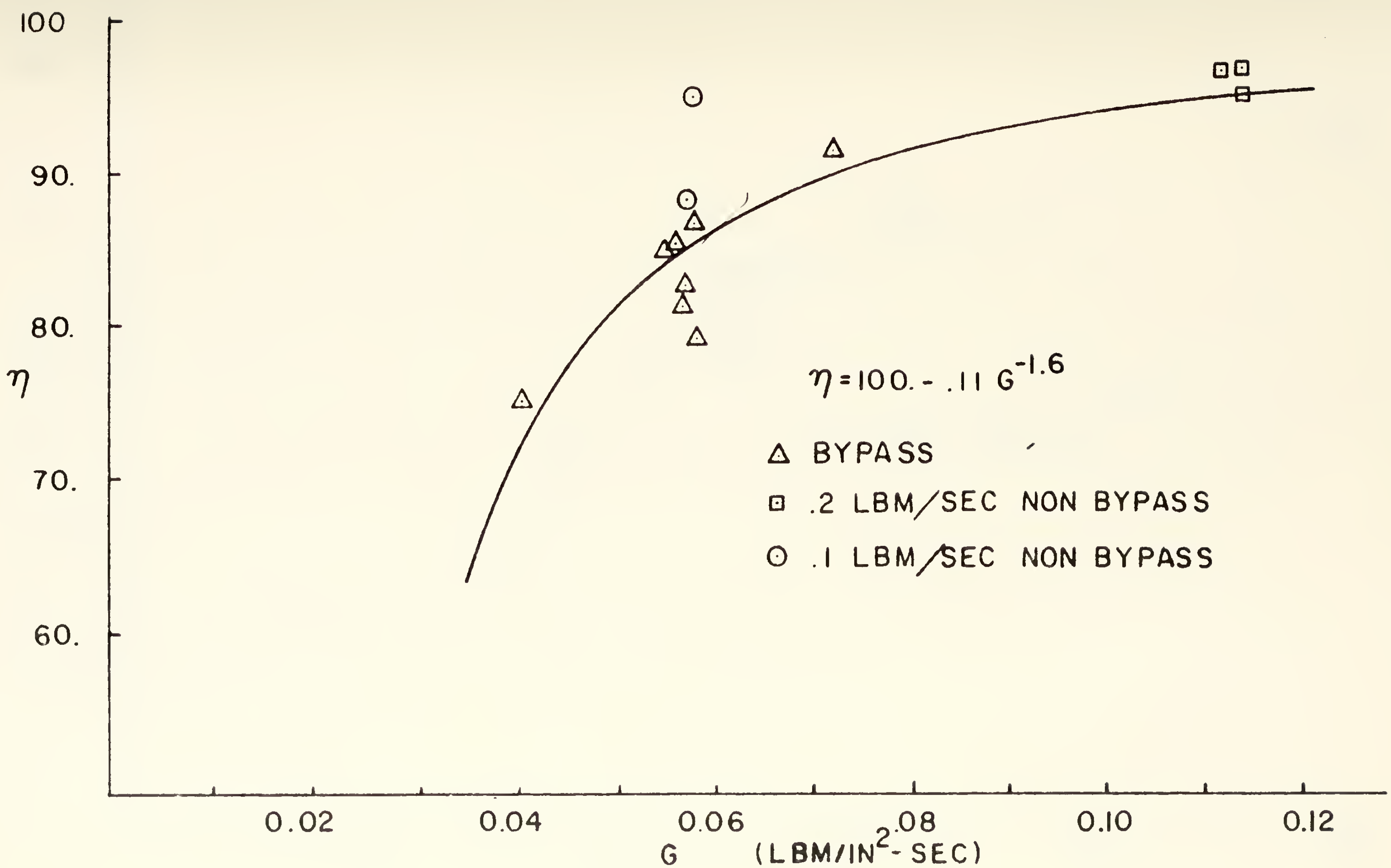


Figure 9 - COMBUSTION EFFICIENCY VS. AIR FLUX RATE

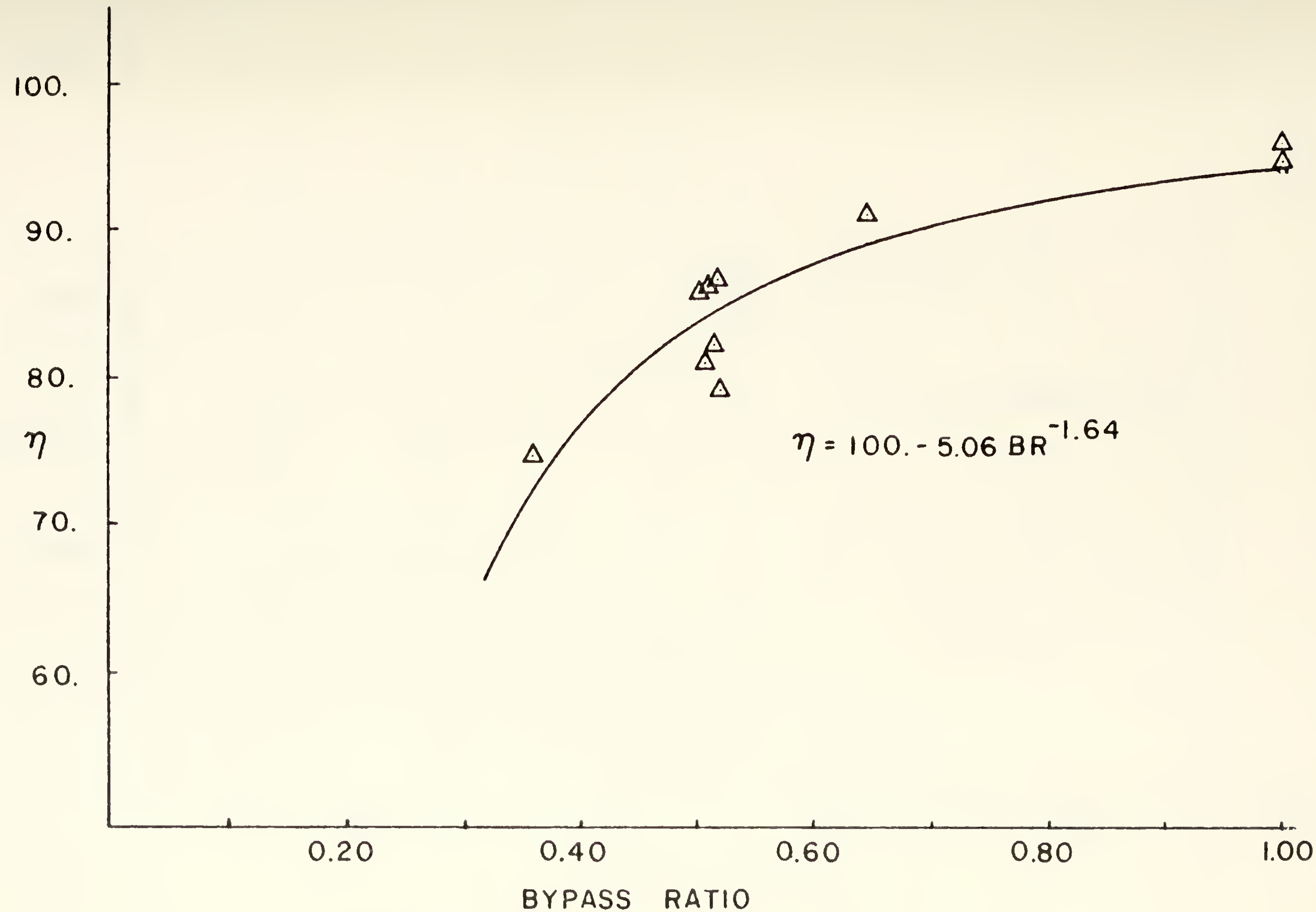


Figure 10 - COMBUSTION EFFICIENCY VS. BYPASS RATIO

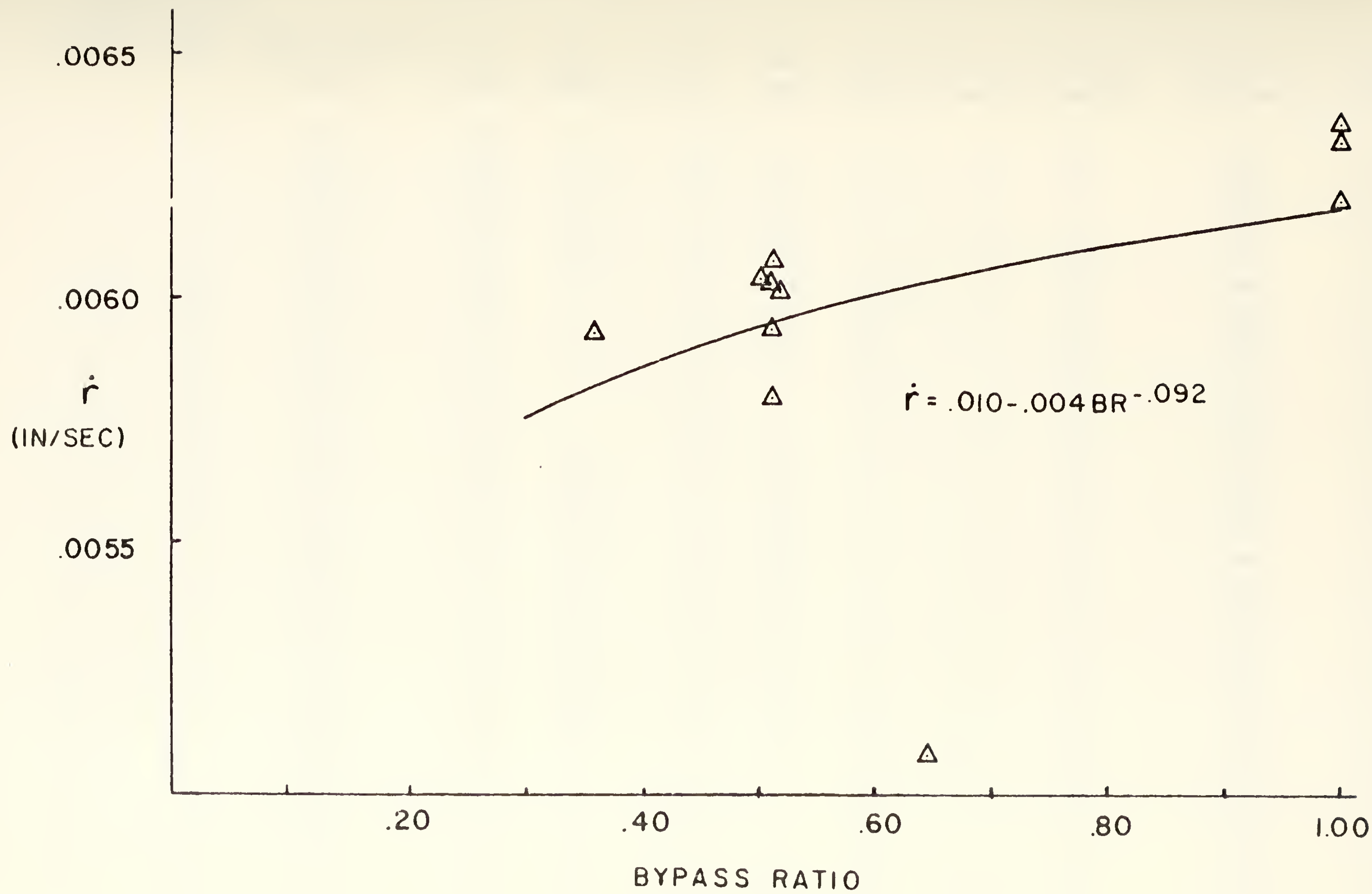


Figure 11 - REGRESSION RATE VS. BYPASS RATIO

APPENDIX A: RAMJET DATA REDUCTION

MEASURED DATA

RUN	GRAIN	ATMOS. PRESS. (psia)	P1 (psig)	P2 (psig)	DP1 (psi)	DP2 (psi)	T1 (Deg-F)	T2 (Deg-F)	T-inlet (Deg-F)	Orifice 1 (inches)	Orifice 2 (inches)
3	8	14.63	133	-	8.5	-	61	61	80	.504	.352
4	3	14.63	132	130	2.0	8.9	59	59	65	.504	.352
5	5	14.63	132	131	2.2	9.2	59	59	65	.504	.352
6	7	14.67	130	129	2.1	8.9	55	55	62	.504	.352
7a	9	14.67	131	131	2.0	9.0	55	55	62	.504	.352
7b	11	14.65	131	130	1.9	9.0	55	55	62	.504	.352
8	10	14.65	130	-	8.7	-	55	55	63	.504	.352
9	12	14.65	132	131	3.1	13.5	327	353	243	.504	.352
10	13	14.63	131	-	13.0	-	325	-	246	.504	.352
11	14	14.60	131	-	8.6	-	60	60	75	.504	.352
12	15	14.58	132	-	2.3	-	60	60	75	.504	.352
13	15	14.62	132	-	2.3	-	60	60	75	.504	.352
14	16	14.61	134	132	2.2	9.0	55	55	65	.504	.352
16	13a	14.60	135	133	2.2	9.0	55	55	65	.504	.352
17	5a	14.64	132	132	2.3	8.8	56	56	62	.504	.352
18	20	14.68	134	133	2.8	9.0	56	56	61	.504	.352
19	21	14.68	134	133	2.3	9.0	57	57	66	.504	.352
20	22	14.69	133	132	2.3	8.9	56	56	62	.504	.352
21	23	14.68	134	134	2.3	8.7	56	56	61	.504	.352
22	24	14.68	133	133	3.5	4.5	56	56	61	.504	.352
23	26	14.67	133	133	1.1	9.1	57	57	65	.504	.400
24	27	14.63	133	132	2.2	5.3	56	56	61	.504	.400
25	28	14.63	133	132	2.2	5.3	56	56	65	.504	.400
26	29	14.63	137	-	2.2	-	57	57	70	.504	.400
27	30	14.62	133	-	8.5	-	57	57	68	.504	.400
28	31	14.56	135	-	2.2	-	56	56	60	.504	.400
29	32	14.56	134	132	2.2	5.5	58	58	64	.504	.400
30	33	14.55	134	131	2.1	5.3	58	58	65	.504	.400
31	34	14.55	133	131	2.2	9.3	58	58	61	.504	.352
32	35	14.68	133	130	2.1	9.3	57	57	65	.504	.352
33	36	14.67	133	131	2.1	9.3	56	56	62	.504	.352

MEASURED DATA

RUN	INIT.WT. (grams)	FINAL.WT (grams)	LENGTH (inches)	INIT.I.D. (inches)	FINAL.I.D. (inches)	BURN TIME (secs.)	IGN.TIME (secs.)	INLET PRESS. (psig)	COMB.PRESS. (psig)
3	2583.2	2202.7	12.00	1.497	2.068	44.9	6.9	48	43
4	2704.6	2347.0	12.00	1.501	1.991	44.8	8.2	41	38
5	2698.5	2375.7	12.00	1.502	1.971	44.7	8.3	36	34
6	2545.4	2188.8	11.99	1.501	2.050	44.8	7.6	44	38
7a	2670.0	2596.6	11.99	1.501	1.602	10.4	7.8	40	34
7b	2492.4	2146.1	11.89	1.510	1.996	44.6	6.6	42	35
8	2531.8	2163.0	11.99	1.499	2.071	44.8	7.1	51	43
9	2743.3	2370.5	11.97	1.497	2.039	44.5	6.5	45	39
10	2582.3	2083.2	11.99	1.507	2.255	44.6	5.7	60	50
11	2510.0	2346.9	12.00	1.500	1.759	19.7	5.4	49	42
12	2640.0	2544.6	12.00	1.503	1.646	19.2	4.6	19	15
13	2486.3	2384.7	12.00	1.753	1.893	19.3	4.4	20	17
14	2739.6	2404.0	12.00	1.502	1.990	44.2	3.7	41	36
16	2721.0	2669.0	11.95	1.500	1.579	7.3	5.8	38	35
17	2566.7	2253.0	11.99	1.516	1.949	44.7	6.3	39	35
18	2611.1	2329.1	12.00	1.512	1.956	44.6	4.5	43	38
19	2624.2	2367.2	12.00	1.512	1.914	44.5	4.6	39	32
20	2624.5	2332.5	12.00	1.517	1.918	44.5	5.1	41	34
21	2541.2	2183.7	12.00	1.515	2.003	44.6	4.5	47	40
22	2557.2	2263.0	12.01	1.517	1.994	44.6	4.5	43	37
23	2573.0	2243.3	11.99	1.518	1.934	41.6	5.8	40	35
24	2435.7	2088.6	11.99	1.522	2.001	43.6	8.8	45	38
25	2619.1	2256.2	12.00	1.520	2.009	44.6	8.2	44	38
26	2578.3	2341.7	11.98	1.514	1.844	44.4	7.2	20	18
27	2345.3	1968.3	11.98	1.512	2.109	44.5	6.2	51	44
28	2427.0	2203.0	12.00	1.516	1.850	44.6	4.6	19	16
29	2576.1	2311.0	12.00	1.515	1.888	44.7	4.2	37	34
30	2631.0	2280.0	12.00	1.514	1.990	44.6	4.2	44	37
31	2559.0	2210.5	12.00	1.511	2.002	44.6	3.6	44	37
32	2541.5	2177.9	11.99	1.510	1.985	44.6	5.7	46	40
33	2707.2	2340.0	11.97	1.499	1.970	44.7	5.0	46	39

MEASURED DATA

RUN	DUMP AXIAL POSITION	DUMP DIAM. (inches)	CONFIGURATION
3	-	-	no bypass
4	fwd	.813	2 @ 180
5	aft	.813	2 @ 180
6	fwd	.813	2 @ 180
7a	aft	.813	2 @ 180
7b	aft	.813	2 @ 180
8	-	-	no bypass
9	fwd	.813	2 @ 180
10	-	-	no bypass
11	-	-	no bypass
12	-	-	no bypass
13	-	-	no bypass
14	fwd	.813	2 @ 180
16	fwd	1.063	2 @ 180
17	fwd	1.063	2 @ 180
18	fwd	1.063	2 @ 90
19	fwd	.751	4 @ 90
20	fwd	.574	4 @ 90
21	fwd	.813	2 @ 180
22	fwd	.574	2 @ 180
23	fwd	1.063	2 @ 180
24	fwd	.574	2 @ 180
25	fwd	.813	2 @ 180
26	-	-	no bypass
27	-	-	no bypass
28	-	-	no bypass
29	fwd	.250	2 @ 180
30	fwd	.813	2 @ 180
31	fwd	.813	2 @ 180
32	fwd	.813	swirl
32	fwd	.813	swirl

REDUCED DATA

RUN	PRI. FLOW RATE (lbm/sec)	BYPASS FLOW RATE (lbm/sec)	FUEL FLOW RATE (lbm/sec)	G-AIR (lbm/in^2-sec)	PHI	COMB. EFF.	C^* EFF.
3	.200	-	.019	.114	.762	93.6 95.0	99.3 99.9
4	.098	.098	.017	.055	.731	83.0 86.3	94.4 95.9
5	.102	.100	.016	.057	.642	80.5 83.8	93.4 95.0
6	.100	.098	.017	.057	.722	83.8 86.9	94.8 96.2
7a	.098	.099	.015	.055	.621	79.8 83.2	93.2 94.7
7b	.097	.099	.017	.054	.714	74.2 78.6	90.2 92.4
8	.202	-	.018	.114	.726	96.4 97.2	100.5 100.8
9	.099	.097	.018	.056	.771	77.7 82.1	92.4 94.4
10	.199	-	.024	.111	1.008	99.2 99.5	101.8 101.9
11	.200	-	.018	.113	.740	90.8 92.7	98.1 98.9
12	.104	-	.012	.058	.850	82.0 85.9	93.9 95.7
13	.104	-	.011	.043	.903	89.1 91.8	97.2 98.4
14	.104	.100	.018	.059	.674	75.1 79.3	90.8 92.8
16	.104	.100	.015	.059	.602	79.9 83.2	93.2 94.7
17	.105	.099	.015	.058	.619	79.0 82.5	92.8 94.4
18	.117	.100	.014	.065	.525	62.8 66.5	84.1 86.1
19	.106	.100	.013	.059	.505	60.3 63.5	83.0 84.8
20	.106	.099	.014	.058	.577	77.0 80.4	91.9 93.5
21	.105	.099	.018	.058	.710	84.2 87.2	95.0 96.4
22	.130	.072	.014	.072	.590	89.8 91.5	97.7 98.5
23	.073	.130	.017	.040	.692	70.2 75.0	88.4 90.7
24	.103	.100	.017	.057	.702	79.0 82.8	92.6 94.4
25	.103	.100	.018	.057	.720	78.8 82.7	92.5 94.3
26	.105	-	.012	.058	.911	94.0 95.5	99.4 100.1
27	.201	-	.019	.112	.759	96.3 97.1	100.5 100.9
28	.104	-	.011	.058	.868	85.1 88.4	95.3 96.9
29	.102	.101	.013	.057	.524	69.5 72.8	88.0 89.7
30	.101	.099	.017	.056	.709	77.7 81.6	92,0 93.8
31	.103	.101	.017	.058	.692	77.6 81.5	91.9 93.8
32	.101	.102	.018	.056	.729	84.8 87.7	95.2 96.6
33	.101	.101	.018	.057	.734	81.7 85.1	93.8 95.4

REDUCED DATA

RUN	REGRESS.RATE (in/sec)X10^3	Tt_5-ACT. (Deg-R)	Tt_5-IDEAL (Deg-R)	BYPASS RATIO	TOT. MOM.	IND. MOM.	DUMP MACH NO.
3	6.37	3512	3669	1.000	.0	.0	.0
4	6.03	3133	3549	.499	.965	.965	.045
5	5.52	2757	3188	.503	1.003	1.003	.048
6	6.03	3119	3512	.504	.966	.966	.044
7a	5.85	2660	3093	.496	1.015	1.015	.050
7b	5.92	2847	3482	.494	.983	.983	.048
8	6.21	3473	3559	1.000	.0	.0	.0
9	6.33	3249	3804	.506	.933	.933	.054
10	8.00	4145	4160	1.000	.0	.0	.0
11	6.75	3367	3588	1.000	.0	.0	.0
12	4.15	3456	3936	1.000	.0	.0	.0
13	3.82	3717	4003	1.000	.0	.0	.0
14	5.80	2736	3313	.510	.992	.992	.047
16	5.95	2649	3079	.510	.587	.587	.028
17	5.36	2655	3108	.516	.570	.570	.028
18	4.90	2726	3838	.538	.586	.586	.027
19	4.52	2499	3631	.514	.586	.293	.030
20	5.05	2554	3049	.516	.987	.493	.049
21	6.03	3083	3460	.515	.977	.977	.043
22	5.07	2915	3137	.645	1.026	1.026	.066
23	5.94	2676	3392	.360	.990	.990	.037
24	5.96	2926	3427	.509	1.992	1.992	.091
25	6.08	2988	3504	.509	.994	.994	.045
26	4.19	3842	3998	1.000	.0	.0	.0
27	6.34	3559	3650	1.000	.0	.0	.0
28	3.97	3558	3956	1.000	.0	.0	.0
29	4.62	2603	3379	.501	10.844	10.844	.532
30	5.94	2922	3463	.505	.983	.983	.046
31	5.92	2857	3388	.506	1.015	1.015	.046
32	6.14	3169	3540	.501	1.011	1.011	.044
33	6.23	3107	3560	.500	1.020	1.020	.045

APPENDIX B

THEORETICAL PERFORMANCE FOR PMM-AIR

Equations for the calculation of the equilibrium gas constant (ft-lbf/lbm-°R), ratio of specific heats, and combustion temperature (°F) as a fuction of inlet temperature (°R), combustion pressure (psia) and air-fuel ratio for Polymethylmethacrylate and air.

Pc = 50 Ti = 500

R = 85.9609 + af *(-8.7617 + af *(0.7589 -0.0215 * af))

g = 1.449914 + af *(-0.059068 + af *(0.0055187 - 0.0001566 * af))

T = 503.7493 + af *(180.1897 + af *(141.7147 + af *(-20.1361 + 0.7044 * af)))

Pc = 100 Ti = 500

R = 86.0584 + af *(-8.7582 + af *(0.7585 - 0.0214 * af))

g = 1.43718 + af *(-0.053096 + af *(0.004661 - 0.0001187 * af))

T = 7272.9547 + af *(-3858.64 + af *(991.307 + af *(-95.2704 + 3.0781 * af)))

Pc = 50 Ti = 750

R = 85.7005 + af *(-8.6698 + af *(0.7506 - 0.0213 * af))

g = 1.440205 + af *(-0.056445 + af *(0.00528 - 0.00015 * af))

T = 95.53247 + af *(489.4649 + af *(80.678 + af *(-15.1934 + 0.56511 * af)))

Pc = 100 Ti = 750

R = 85.8749 + af *(-8.7313 + af *(0.7561 - 0.0215 * af))

g = 1.44198 + af *(-0.057074 + af *(0.005337 - 0.000152 *

af))

T = 397.8427 + af *(308.8051 + af *(117.7353 + af *(-18.2495 + 0.6523 * af)))

Pc = 50   Ti = 1000

R = 85.4012 + af *(-8.565 + af *(0.7416 - 0.0211 * af))

g = 1.430833 + af *(-0.053936 + af *(0.005058 - 0.0001449 * af))

T = 501.175 + af *(364.7408 + af *(99.204 + af *(-16.202 + 0.582 * af)))

Pc = 100   Ti = 1000

R = 86.0304 + af *(-8.8284 + af *(0.7739 - 0.0224 * af))

g = 1.42658 + af *(-0.05177 + af *(0.0047196 - 0.0001292 * af))

T = 4721.969 + af *(-2203.3985 + af *(651.3712 + af *(-66.083 + 2.1875 * af)))

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